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Journal of Magnetism and Magnetic Materials 256 (2003) 41–45

journal of magnetism and magnetic materials

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Influence of the initial temperature on the thermal remagnetization of $SmCo_5$ sintered magnets

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Received 1 August 2001; received in revised form 2 January 2002

Abstract

Modern permanent magnets show an irreversible increase of the remanent magnetization for increasing temperature. This thermal remagnetization (TR) occurs after DC-demagnetization at the initial temperature T_0 followed by heating. The TR is especially large for well-aligned sintered $SmCo_5$ permanent magnets and is strongly correlated with the grain-interaction and the temperature coefficient of the coercivity. We present a systematical study on the influence of the initial temperature T_0 on the TR of $SmCo_5$ sintered magnets experimentally and theoretically. We find that the TR-maximum increases with decreasing T_0, whereas its position $T_{\max}$ shits slightly to lower temperatures with decreasing T_0. This together with the dependence on the sample demagnetization factor N, is in agreement with the results of our model calculation. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 75.50.Vv; 75.50.Ww; 75.60.Ej

Keywords: Permanent magnets; Thermal remagnetization; Grain interaction; Internal field; Fluctuations; Switching field distribution

1. Introduction

The thermal remagnetization (TR) is an interesting irreversible magnetization process [1–10], which influences the thermal stability of partly DC-demagnetized, nucleation-controlled permanent magnets with high uniaxial crystalline anisotropy. It was investigated with different kinds of hard magnets, e.g. [2,5,8,12] and is especially large for $SmCo_5$-sintered magnets [2,4,6,12]. The TR is observed if the magnet is heated to a certain temperature $\leqslant T_{\max}$, starting after saturation and reaching the DC-demagnetized state at the initial temperature T_0. The main feature of this process is an at first gradual and later strong increase of the sample remanence with increasing temperature in zero external field. On further increasing the temperature the magnetization drops rapidly. The reasons for the TR are the change of the distribution of the switching fields of the hard magnetic grains, the modifications of the local internal field by grain interactions as well as the

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PII: S0304-8853(02)00019-7

temperature dependence of the switching field. The magnetization of the "hardest grains" persists in the direction of the initial saturation (plus-direction) in a wide temperature range up to T_{max}. Less hard or "weak" grains, which changed their magnetization during the DC-demagnetization into the minus-direction, are switched back into the plus-direction. The temperature dependence of the switching field is related to the temperature dependence of both the coercivity $H_c(T)$ and the saturation magnetization $M_s(T)$. It was shown that in the case of well-aligned $SmCo_5$-sintered magnets of medium coercivity [6] the TR is maximum and that in a closed magnetic circuit ($N = 0$) to 100% of $M_s(T_{max})$ can be regained, which corresponds after cooling up to 100% of $M_s(T_0)$ [2]. Due to the technical applications of the magnets in most investigated cases the room temperature was chosen as the initial temperature. In Ref. [3] also lower initial temperatures are mentioned. In the present study we have varied the initial temperature T_0 in a wide range between 5 and 450 K and compare the results with outer model calculations [11].

2. Experimental results

We investigated disks of about 5 mm diameter of sintered $SmCo_5$-magnets (Vacomax 200) with a sample demagnetization factor $N \approx 0.5$. The magnetic measurements have been performed in an Oxford Mag-Lab (14 T) vibrating sample magnetometer (VSM) in both the low-temperature and the high-temperature modification. The sweep rates were about 1 T/min and about 1 K/min. The magnetization measurements were started by saturation in fields up to 12 T at the initial temperature T_0. Then the isothermal demagnetization curve was recorded up to the remanence coercivity H_R and the DC-demagnetized state was reached over the recoil curve (Fig. 1). During the TR-experiment the sample was slowly heated in zero external field up to T_{max}. The saturation- and DC-demagnetization procedure was repeated for each temperature T_0. Fig. 2 shows the influence of heating on the sample remanence in zero external field for three low initial temperatures T_0. The maximum temperature of about 300 K was limited by the low-emperature option of the VSM. The three curves shown in Fig. 2 demonstrate the initial irreversible TR-effect at very low temperatures in a high-coercivity region. In Fig. 3 three TR-curves up to the maximum of the TR-process at about 690 K are shown, measured with the high-temperature option of the VSM. By cooling from this maximum temperature the magnetization increases reversibly following exactly the $M_s(T)$-curve. We observe only a small shift of the maximum position to lower temperatures, if the initial temperature T_0 decreases. On the other hand, the influence of T_0 on the maximum of the

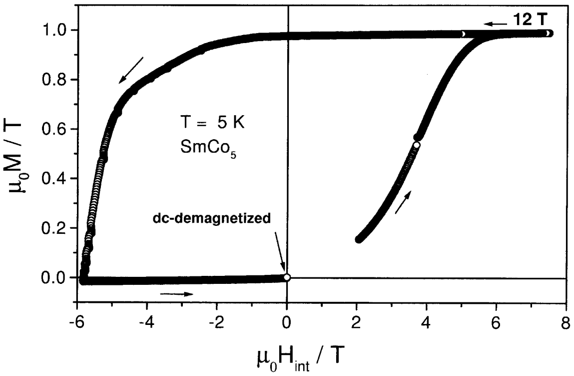

Fig. 1. Process to obtain the DC-demagnetized state at the initial temperature $T_0 = 5$ K ($SmCo_5$-magnet, Vacomax 200).

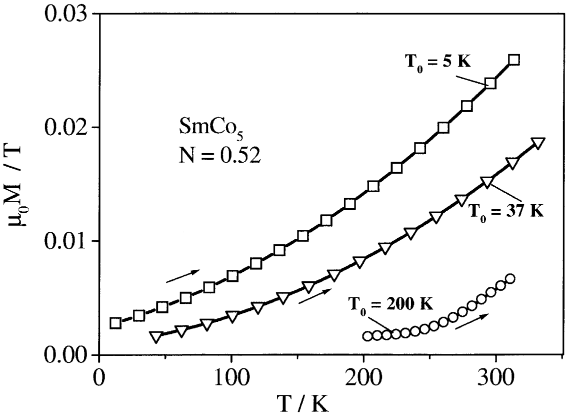

Fig. 2. Remanence enhancement for three lower initial temperatures T_0 ($SmCo_5$-magnet, Vacomax 200).

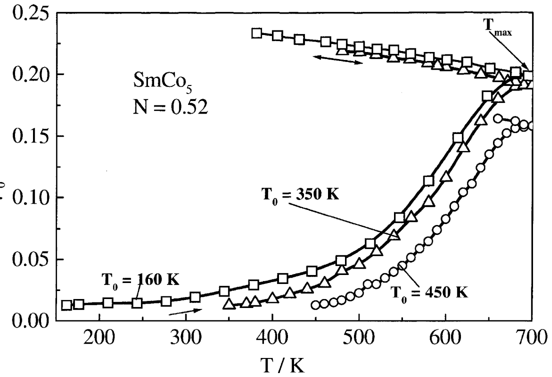

Fig. 3. TR-experiments as shown in Fig. 2 up to the TR-maximum at $T_{\max}$ for higher initial temperatures T_0.

irreversible remanence enhancement is rather pronounced (Fig. 3).

3. Theoretical calculation

For the theoretical calculations after the new model [11] we assumed an ensemble of perfectly aligned bistable volume units ("grains"). Their switching fields H_s are distributed according to a Gaussian with the maximum at $\langle H_s \rangle$ and the width σ_s. The internal field in a grain is given by the local field H via

$$H_{\text{int},\alpha} = H - n(\alpha M_S - \langle M \rangle), \tag{1}$$

n being an averaged demagnetization factor of the grains. Although the introduced n-values of the "grains" in reality also are broadly distributed, we neglect this for simplicity up to now in the theoretical model [11]. $\langle M \rangle$ is the averaged sample magnetization and $\alpha = \pm 1$ the switching variable. The local field H at the position of a grain fluctuates around the mean field:

$$\langle H \rangle = H_{\text{ext}} - N \langle M \rangle, \tag{2}$$

where N is the demagnetization factor of the sample. We assume that the local fields are Gaussian distributed around $\langle H \rangle$. In addition, we assume that the distribution width of $\langle H \rangle$ depends on $\langle M \rangle$ according to

$$\sigma_f(\langle M \rangle) = \sigma_f \left(1 - \left(\frac{\langle M \rangle}{M_S} \right)^2 \right). \tag{3}$$

Eq. (3) takes into account that the field fluctuations in the DC-demagnetized state and also the grain interactions are maximum, whereas the fluctuations vanish in the saturated state. A grain is switched, if its internal field after Eq. (1) overcomes its switching field H_s. The calculation starts at saturation. Then follows the demagnetization curve up to $-H_R$. Finally, the recoil curve to zero remanence is computed. An increase in temperature results in a decrease in the switching field of the grains, approximately given by the temperature dependence of the coercivity (cf. Eq. (4)). Those grains from the lower field side of the switching field distribution that are downwards magnetized by the isothermal DC-demagnetization firstly fulfill the switching condition and thus produce the TR up to $T_{\max}$.

For higher temperatures also those grains that resisted the DC-demagnetization procedure reduce their switching fields drastically. Thus finally, the grain-magnetization directions become random and the averaged magnetization decreases to zero. According to Eq. (1), H_{int} is dependent on the sample magnetization, hence the calculation has to be done self-consistently [11].

Examples of calculated TR-curves are given in Ref. [11]. Here we will focus on the TR-curves for different N-values and for different T_0 given in Figs. 4 and 5, respectively. They are computed with the experimentally determined $M_S(T)$- and

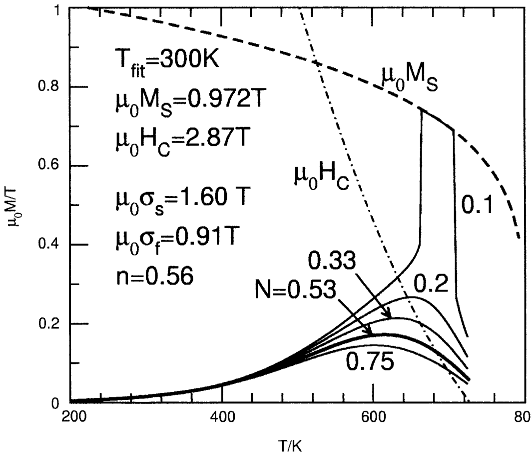

Fig. 4. Calculated TR-curves for different sample demagnetization factors N and the other inserted parameters.

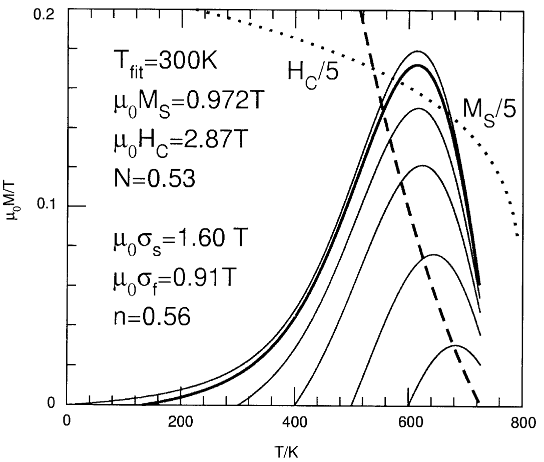

Fig. 5. Calculated TR-curves for a typical $SmCo_5$-sample for different initial temperatures T_0 using the other inserted parameters.

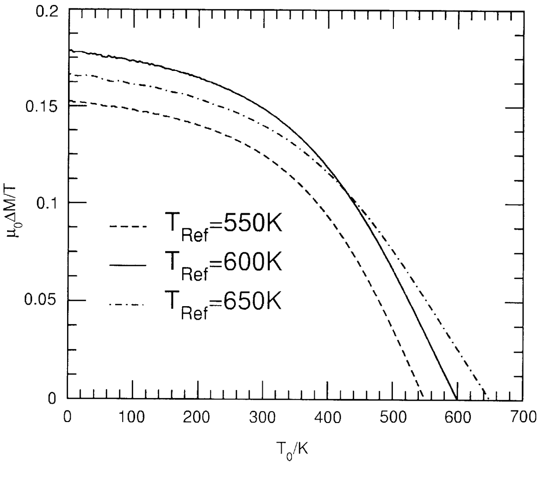

Fig. 6. Influence on the initial temperature T_0 on the maximum remanence enhancement for three different reference temperatures T_{ref}.

$H_C(T)$-curves and with the parameter set as given in Fig. 5, determined by a fit to the measured TR-curves for $T_0 = 132\,\mathrm{K}$ [11].

$\langle H_s \rangle(T)$ was computed self-consistently according to the formalism explained in detail in Ref. [11]. A good approximation for our parameter sets in given by [11]

$$\langle H_s \rangle(T) = H_C(T) + nM_S(T). \tag{4}$$

On decreasing the sample demagnetization factor N, the TR-maximum increases and reaches 100% for a nearly closed magnetic circuit. This dependence is given in Fig. 4 for an initial temperature of $T_0 = 200\,\mathrm{K}$. As evident from this figure, N further influence both the maximum value and the temperature $T_{\max}$. An essential parameter is found to be σ_f. We estimated it to be $\sim 0.9\,\mathrm{T}$ for $SmCo_5$ [11]. In Fig. 5 we present calculated TR-curves for different initial temperatures T_0. The explicit dependence of the TR-effect between T_0 and a certain reference temperature T_{ref} is given in Fig. 6.

4. Conclusions

The semi-quantitative agreement of the TR-experiments for the $SmCo_5$-sintered magnets with the presented model [11] allows some conclusions:

- The effect of the TR at DC-demagnetized $SmCo_5$-magnets already occurs in the low-temperature region, where the coercivity is very large compared to the saturation magnetization.
- The observed and calculated TR-maximum increases whereas the position $T_{\max}$ decreases with decreasing initial temperature T_0 (Figs. 3 and 5). This influence is theoretically expected for measurements in an open magnetic circuit ($N > 0$). The TR-effect is larger for smaller sample demagnetizing factors N (cf. Fig. 4) and maximum in a closed circuit, as already known from Ref. [2]. But the shift of the maximum position ($T_{\max}$) and the shape of the TR-curves are more influenced by the internal parameters n and σ_f, which also determine the recoil curves.
- Besides n, the parameters σ_f, the fluctuation width of the local field H, could be determined roughly from the comparison of the TR-experiments with the model calculations. We found σ_f-values of 0.9 T for $SmCo_5$ at 300 K [11]. We regard this parameter as an essential characteristic of the hard magnetic sample in its DC-demagnetized state.

Acknowledgements

We acknowledge the support by the Deutsche Forschungsgemeinschaft, Grants LO 293/1-1 and 436 rus 17/119/98 and thank Dr. W. Rodewald (Vacuum-schmelze Hanau) for the supply of the permanent magnets.

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